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## Explaining the Flavor Anomalies with a Vector Leptoquark (Moriond 2019 update)

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# Explaining the Flavor Anomalies with a Vector Leptoquark (Moriond 2019 update)

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Several experiments revealed intriguing hints for lepton flavor universality (LFU) violating new physics (NP) in semi-leptonic  $B$  meson decays, mainly in  $b \rightarrow c\tau\nu$  and  $b \rightarrow s\ell^+\ell^-$  transitions at the  $3 - 5\sigma$  level. Leptoquarks (LQ) are prime candidates to address these anomalies as they contribute to semi-leptonic decays already at tree level while effects in other flavor observables, agreeing with the standard model (SM), are loop suppressed.

In these proceedings we review the vector leptoquark  $SU(2)_L$  singlet, contained in the famous Pati-Salam model, which is able to address both  $b \rightarrow c\tau\nu$  and  $b \rightarrow s\mu^+\mu^-$  data simultaneously. Due to the large couplings to tau leptons needed to account for the  $b \rightarrow c\tau\nu$  data, sizable loop effects arise which we include in our phenomenological analysis. Updating our result of Ref. [1] with the recent measurements of LHCb [2] and BELLE [3, 4] we find an even better fit to data than before.

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## 1. Introduction

While so far the LHC has not detected any particles beyond the ones present in the Standard Model (SM), intriguing hints for LFU violation in semi-leptonic  $B$ -meson decays were accumulated in several (classes of) observables:

$$b \rightarrow s \ell^+ \ell^-$$

In these flavor changing neutral current transitions, measurements of the ratios

$$R(K^{(*)}) = \frac{\text{Br}[B \rightarrow K \mu^+ \mu^-]}{\text{Br}[B \rightarrow K e^+ e^-]}$$

show sizable deviations from their respective SM prediction. While the newest measurement of  $R(K)$  by the LHCb collaboration [2] shows a deviation of  $2.5 \sigma$  from the SM, the Belle result for  $R(K^{(*)})$  is consistent with the SM [3]. However, due to the larger errors, this result also agrees with previous LHCb measurements of  $R(K^{(*)})$  which deviate from the SM [5] in the same direction as  $R(K)$ . Taking into account all other  $b \rightarrow s \mu^+ \mu^-$  observables (like the lepton flavor universal observable  $P'_5$  [6]), the global fit prefers various NP scenarios above the  $5 \sigma$  level [7] compared to the SM, also when the newest measurements are taken into account [8–11].

In order to resolve the discrepancy in the neutral current transitions, an effect of  $\mathcal{O}(10\%)$  is required at the amplitude level. Since this flavor changing neutral current (FCNC) is suppressed in the SM as it is only induced at one loop level, a small NP contribution is already sufficient. In a global fit one finds a preference for scenarios like  $C_9^{\mu\mu} = -C_{10}^{\mu\mu}$  (i.e. a left-handed current coupling to muons only) [8]. Such an effect is naturally obtained at tree-level with the vector LQ  $SU(2)$  singlet [1, 12–32]. However, a  $C_9^{\mu\mu} = -C_{10}^{\mu\mu}$  effect complemented by a flavor universal effect in  $C_9$  gives an even better fit to data [8, 33]. As we will see, this is exactly the pattern that arises in our model.

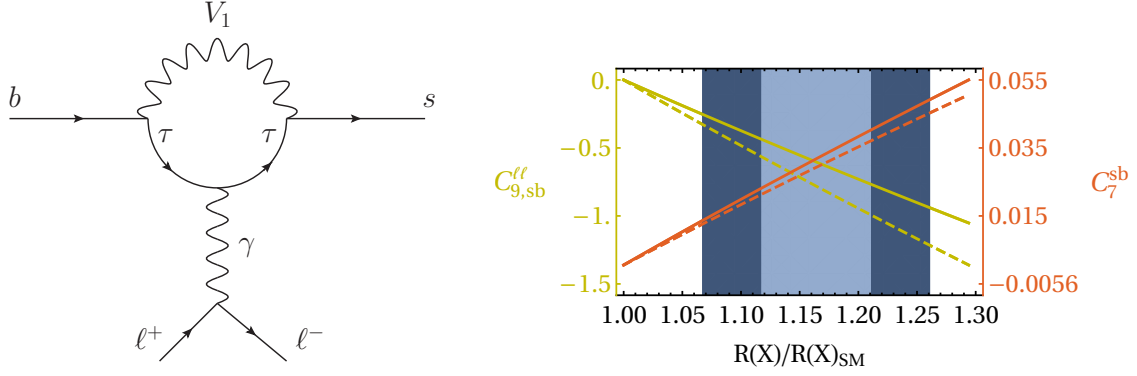
$$b \rightarrow c \tau \nu$$

There are also indications for LFU violation in charged current transitions, namely in the ratios

$$R(D^{(*)}) = \frac{\text{Br}[B \rightarrow D^{(*)} \tau \nu]}{\text{Br}[B \rightarrow D^{(*)} \ell \nu]}$$

where  $\ell = \{e, \mu\}$ . While the newest measurements from Belle [4] agree with the SM prediction, including previous measurements by BaBar, Belle and LHCb still yield a deviation of  $3.1 \sigma$  [34] from the SM prediction. Furthermore there is also a measurement of the ratio  $R(J/\Psi) = \frac{\text{Br}[B_c \rightarrow J/\Psi \tau \nu]}{\text{Br}[B_c \rightarrow J/\Psi \mu \nu]}$  exceeding its SM prediction [35].

Also here a NP effect of  $\mathcal{O}(10\%)$  is needed at the amplitude level. However, since  $b \rightarrow c \tau \nu$  transitions are mediated at tree level by the exchange of a  $W$  boson in the SM, the NP effect needs to be large. This means that NP should contribute at tree level with sizable couplings and at a not too high NP scale. Here, the best single particle solution is the vector LQ  $SU(2)$  singlet [1, 12–32] since it does not give a tree-level effect in  $b \rightarrow s \nu \nu$  processes and provides a common rescaling of  $R(D)$  and  $R(D^*)$  with respect to the SM prediction.



**Figure 1:** Left: Feynman diagram depicting the loop effects induced by the  $bc\tau\nu$  operator from  $SU(2)$  invariance. Right:  $C_{9,9,sb}^{\ell\ell}$  and  $C_7^{sb}(\mu_b)$ , generated by these loop effects, as functions of  $R(D^{(*)})/R(D^{(*)})_{\text{SM}}$ . The solid (dashed) lines correspond to  $M = 1$  TeV (5 TeV) while the (dark) blue region is preferred by  $b \rightarrow c\tau\nu$  data at the  $1\sigma$  ( $2\sigma$ ) level, taking into account the most recent measurements. From the global fit, taking into account only lepton flavor conserving observables, we have  $-1.29 < C_{9,9,sb}^{\ell\ell} < -0.87$  [38] and  $-0.01 < C_7^{sb}(\mu_b) < 0.05$  [7] at the  $1\sigma$  level. Assuming an explanation of  $b \rightarrow c\tau\nu$ , our model predicts the right size and sign of the effect in  $C_{9,9,sb}^{\ell\ell}$  and  $C_7^{sb}(\mu_b)$  needed to explain  $b \rightarrow s\ell^+\ell^-$  data.

## 2. The Pati Salam vector leptoquark as combined solution to the anomalies

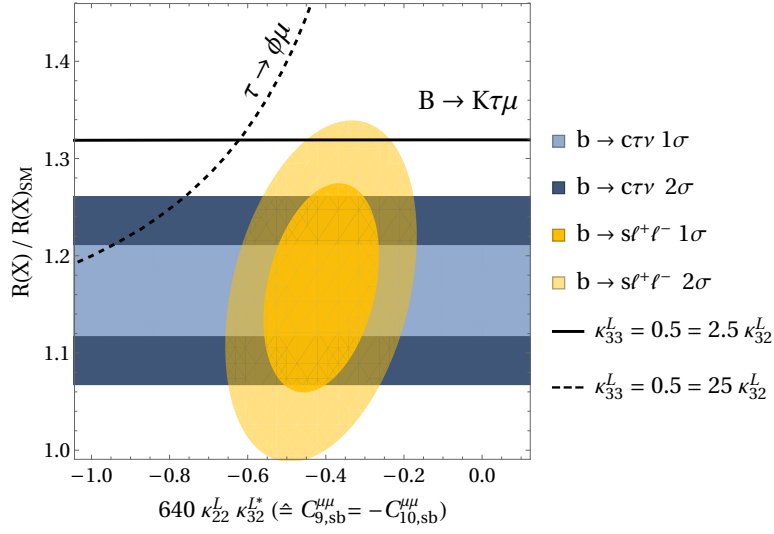
The vector Leptoquark  $SU(2)_L$  singlet with hypercharge  $-4/3$ , arising in the famous Pati-Salam model [36], is a prime candidate to explain both the anomalies in charged current and neutral current  $B$  decays simultaneously [12–14, 17–20]. It gives a  $C_9 = -C_{10}$  effect in  $b \rightarrow s\ell^+\ell^-$  at tree level and at the same time a sizable effect in  $b \rightarrow c\tau\nu$  without violating bounds from  $b \rightarrow s\nu\nu$  and/or direct searches and does not lead to proton decay. Note that this LQ by itself is not UV complete, however several UV complete models for this LQ have been proposed [15, 16, 21–29, 37].

For the purpose of our phenomenological analysis, let us consider a model where we simply extend the SM by this LQ. Its interaction with the SM particles is given by the Lagrangian

$$\mathcal{L}_{V_1} = \kappa_{fi}^L \bar{Q}_f \gamma_\mu L_i V_\mu^{1\dagger} + h.c. ,$$

where  $Q(L)$  is the quark (lepton)  $SU(2)_L$  doublet,  $\kappa_{fi}^L$  represents the couplings of the LQ to the left handed quarks (leptons) and  $f$  and  $i$  are flavor indices. Note that in principle couplings to right-handed SM particles are also allowed, they are however not relevant for this discussion. After electro-weak symmetry breaking, we work in the down basis, meaning that no CKM matrix elements appear in FCNC processes.

We start by taking  $\kappa_{23}^L$  and  $\kappa_{33}^L$  as the only non-zero couplings, as they are necessary to explain  $b \rightarrow c\tau\nu$  data. Here, strong effects in  $b \rightarrow s\tau^+\tau^-$  transitions [39] are generated which at the 1-loop level affect  $b \rightarrow s\ell^+\ell^-$  via the Wilson coefficients  $C_{9,9,sb}^{\ell\ell}$  and  $C_7^{sb}$ , as is depicted to the left in Fig. 1. Due to the correlation with  $b \rightarrow c\tau\nu$ , these Wilson coefficients can be expressed as functions of  $R(D^{(*)})/R(D^{(*)})_{\text{SM}}$ . The Wilson coefficients' dependency on these ratios is shown in the right plot of Fig. 1, where the RGE evolution of  $C_7^{sb}$  from the NP scale down to the  $b$  quark scale is also taken into account (see Ref. [40]). Interestingly, assuming an explanation of  $b \rightarrow c\tau\nu$  data, the effects



**Figure 2:** Allowed (colored) regions in the  $C_{9, sb}^{\mu\mu} = -C_{10, sb}^{\mu\mu}$  ( $\equiv 640\kappa_{22}^L \kappa_{32}^{L*}$ )  $- R(X)/R(X)_{SM}$  plane for  $M = 1$  TeV and  $X = \{D, D^*\}$  at the  $1\sigma$  and  $2\sigma$  level. The region above the black dashed (solid) line is excluded by  $\tau \rightarrow \phi\mu$  ( $B \rightarrow K\tau\mu$ ) for  $\kappa_{33}^L = 0.5 = 25\kappa_{32}^L$  ( $\kappa_{33}^L = 0.5 = 2.5\kappa_{32}^L$ ). The bound from  $\tau \rightarrow \phi\mu$  ( $B \rightarrow K\tau\mu$ ) depends on  $\kappa_{33}^L$  and  $\kappa_{32}^L$  and gets stronger if  $\kappa_{32}^L$  gets smaller (larger). That is, for  $\kappa_{33}^L = 0.5$  and  $2.7 \lesssim \kappa_{33}^L/\kappa_{32}^L \lesssim 27$ , the whole  $2\sigma$  region preferred by  $b \rightarrow c\tau\nu$  and  $b \rightarrow s\ell^+\ell^-$  data is consistent with these bounds. Note that we used the most recent experimental results for both the  $b \rightarrow c\tau\nu$  and  $b \rightarrow s\ell^+\ell^-$  transitions, therefore updating our analysis in Ref. [40].

generated in  $C_{9, sb}^{\ell\ell}$  and  $C_7^{sb}$  agree with the  $1\sigma$  ranges of the model independent fit to  $b \rightarrow s\mu^+\mu^-$  data excluding LFU violating observables [38, 41].

Now we also allow  $\kappa_{32}^L$  and  $\kappa_{22}^L$  to be non-zero, generating a tree level effect in  $b \rightarrow s\mu^+\mu^-$  which is necessary to account for the LFU violating observables as well. In Fig. 2 we show the allowed (colored) regions from  $b \rightarrow s\mu^+\mu^-$  and  $b \rightarrow c\tau\nu$  as well as the exclusions from  $b \rightarrow s\tau\mu$  and  $\tau \rightarrow \phi\mu$ . A simultaneous explanation of the anomalies is perfectly possible since the colored regions overlap and do not extend to the parameter space excluded by  $b \rightarrow s\tau\mu$  and  $\tau \rightarrow \phi\mu$ . Interestingly, we predict a lepton flavor universal effect in  $C_{9, sb}^{\ell\ell}$  and  $C_7^{sb}$  in addition to a LFU violating tree-level effect of the form  $C_{9, sb}^{\mu\mu} = -C_{10, sb}^{\mu\mu}$  in muonic channels only. This means that the effect of NP compared to the SM is expected to be larger in lepton flavor universal observables like  $P5'$  relative to LFU violation observables as  $R(K^{(*)})$ , which is in perfect agreement with global fit scenarios [8]. In fact, the agreement is even better after the inclusion of the new measurements of BELLE and LHCb.

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